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DEVELOPMENT OF THE 155MM BALLISTIC
SIMULATOR

James H. Wiland

Frankford Arsenal

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Army Materials and Mechanics Research Center

August 1974

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the development and testing of the 155 mm Ballistic Simulator for laboratory testing of artillery fuzes. Present test methods using a 5 inch air gun are compared with the ballistic shock environment and are shown to have significant limitations. The design approach of the new simulator is described. The new system includes as its basic component a 155 mm field gun and uses compressed air as the high pressure fluid.		

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Provision for shaping the acceleration-time history is included as well as simultaneous rotation of the test item. Initial tests on the 155 mm Ballistic Simulator have been performed up to 12,000 g's and sample acceleration-time histories are shown. It is concluded that within its operating range, the new simulator provides a significantly better simulation of ballistic shock than the present test method.

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INTRODUCTION

One of the most severe environments encountered by military equipment is that experienced by ammunition components during gunfire shock. The shock levels experienced by an artillery projectile may be as high as 56,000 g's in some weapons, with muzzle velocities approaching 5000 feet per second. Because of the severity of gunfire shock and the limited space requirements, ammunition components such as fuzes are required to withstand very high stress levels. Extensive laboratory tests are performed on fuzes to insure their structural reliability and proper functioning under the setback shock environment. Large scale field firing programs are also carried out on both developmental and production fuzes.

Various laboratory test methods have been developed in an effort to reduce the amount of expensive field firings presently conducted to insure fuze reliability. Laboratory testing of fuzes is particularly desirable because the fuze is recovered almost immediately, and is undamaged by any impact such as occurs in field firings. This report describes a Materials Testing Technology Program aimed at developing a ballistic simulator for improving the simulation of gunfire shock, including rotation, in the laboratory testing of artillery ammunition components. The report includes a description of the existing laboratory test method, the design approach used in developing the 155mm Ballistic Simulator, and the test results obtained with the initial system configuration. While a great deal of work must still be done in refining the system, it works, its simulation of gunfire shock is significantly better than the present test method, and the important effects of rotation are included. It is believed that the system will be very useful in the laboratory simulation of artillery gunfire shock, and can be used to advantage in testing fuzes and other ammunition components.

CHARACTERISTICS OF GUNFIRE SHOCK

Reference 1 presents data on artillery gunfire shock for a wide range of weapons from the 40mm to the 280mm gun. Curves are presented for a variety of firing conditions giving projectile acceleration, velocity, and displacement as a function of time. Figure 1, taken from this reference, shows one curve for the 105mm gun; the general shape of the time histories being the same for all guns. For the majority of conditions, the acceleration rises approximately sinusoidally to its peak value in 2 to 4 milliseconds, followed by an exponential type decay, and is positive throughout the length of the gun. The maximum projectile velocity is thus attained at the exit of the gun. In almost every case, the peak acceleration is reached within the first 20 inches of travel. Typically, maximum acceleration is of the order of 20,000 g's, with corresponding muzzle velocities of about 2000 feet per second.

DESCRIPTION OF 5 INCH AIRGUN TEST METHOD

The high forces and large velocity changes typical of gunfire shock dictate that laboratory tests for this environment be performed in a gun-type facility. At Frankford Arsenal, the facility used for shock testing of ammunition components is the 5 Inch Air Gun (Figure 2). This system consists of a 5 inch smooth bore Naval gun with a closed end extension, having an overall length of 56 feet. High pressure air (up to 14,000 psi) is used to propel a piston containing the test item through the barrel. As the piston travels down the barrel, it compresses the low pressure air ahead of it and is brought to a gradual stop. The piston is then slowly returned to the breech for removal and examination of the test item.

The primary method of firing the 5 inch air gun has been the diaphragm method, which is shown in Figures 3 and 4. Initially the diaphragm, with a circular groove machined in its surface, is

¹ L. Heppner, "Special Study of Setback & Spin for Artillery & Tank Ammunition", Aberdeen Proving Ground Report No. DPS-1963, April 1966.

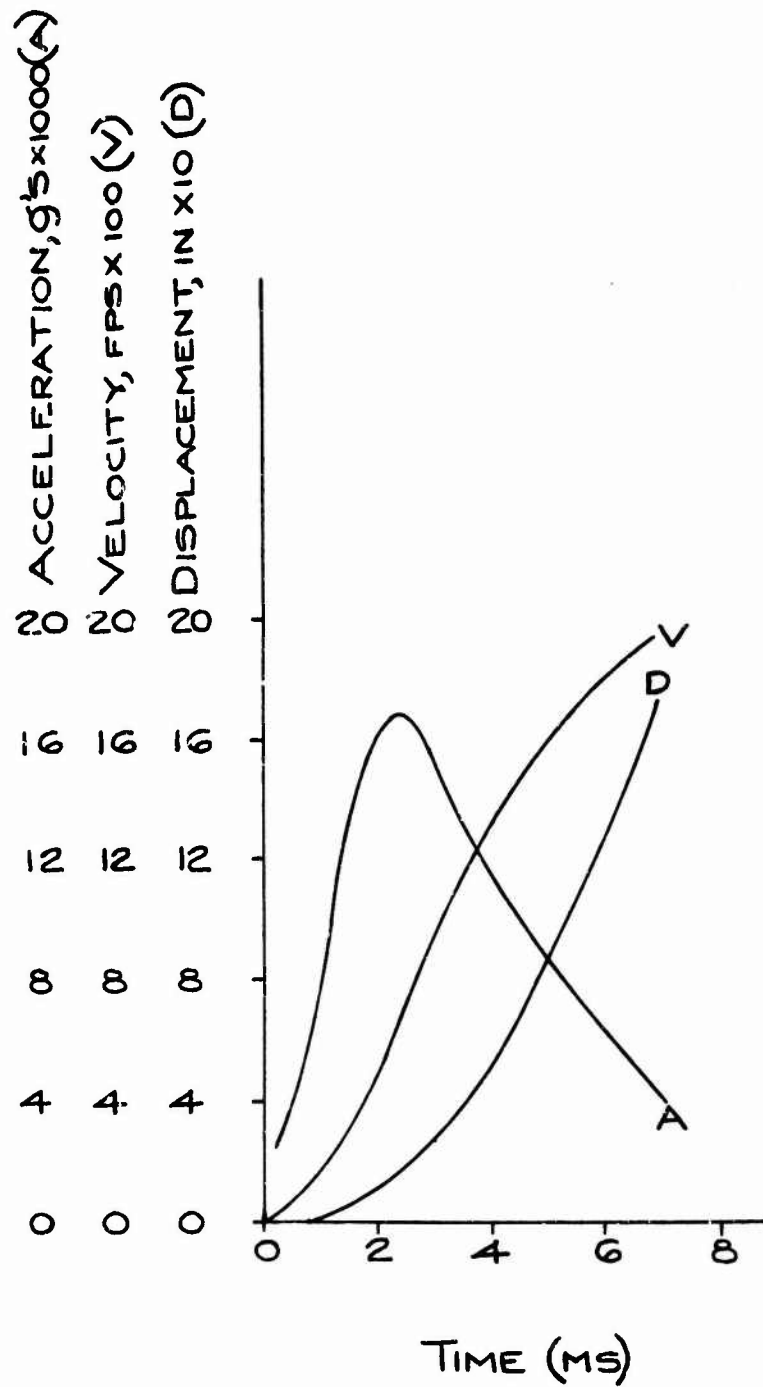


Figure 1. Gunfire Shock

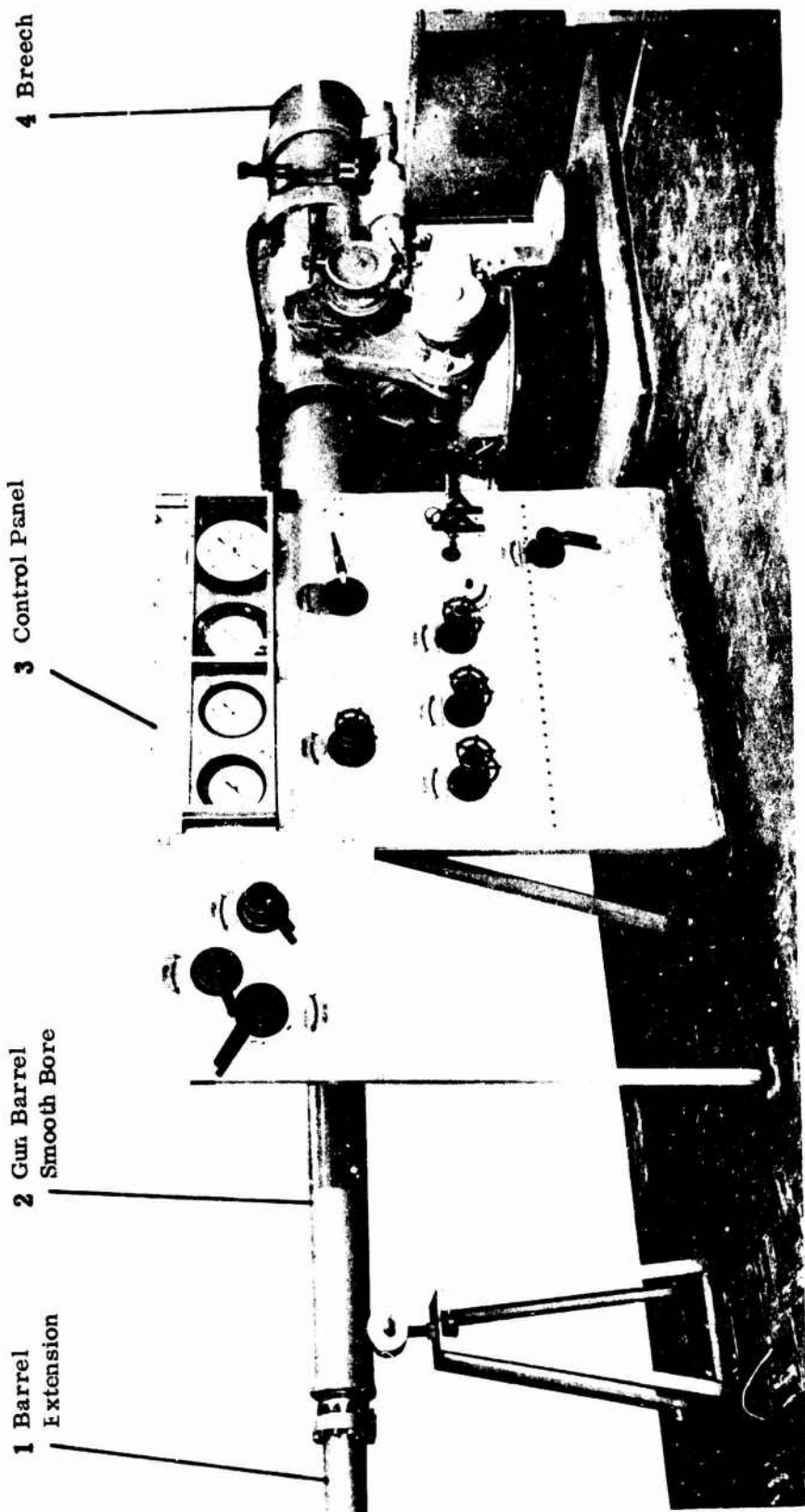


Figure 2. 5 Inch High "G" Air Gun System

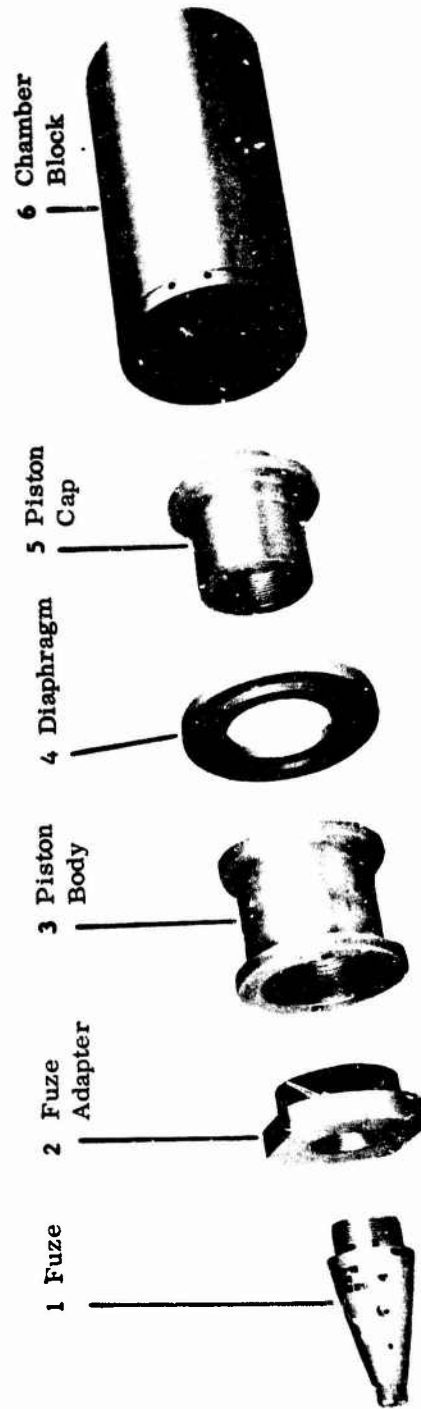
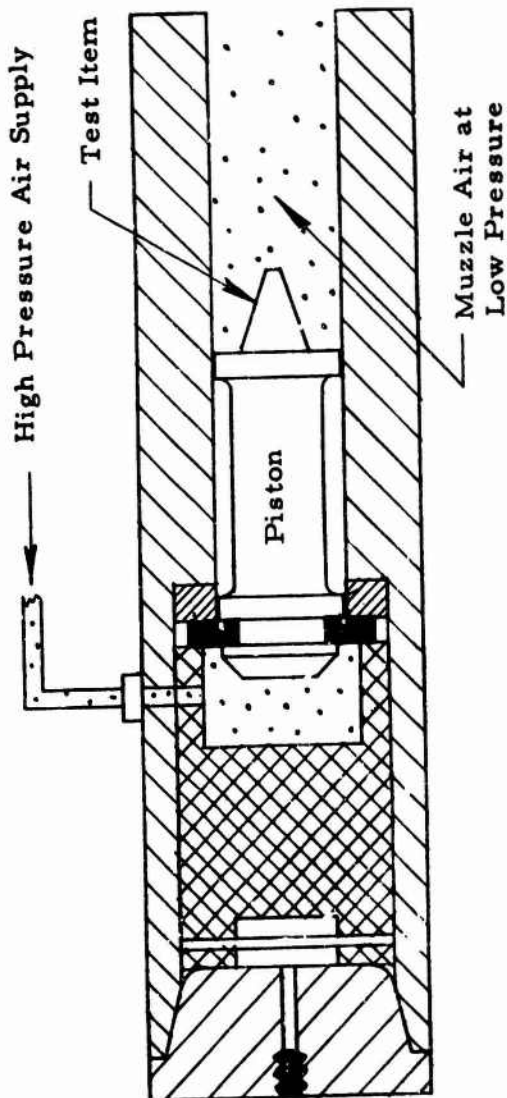
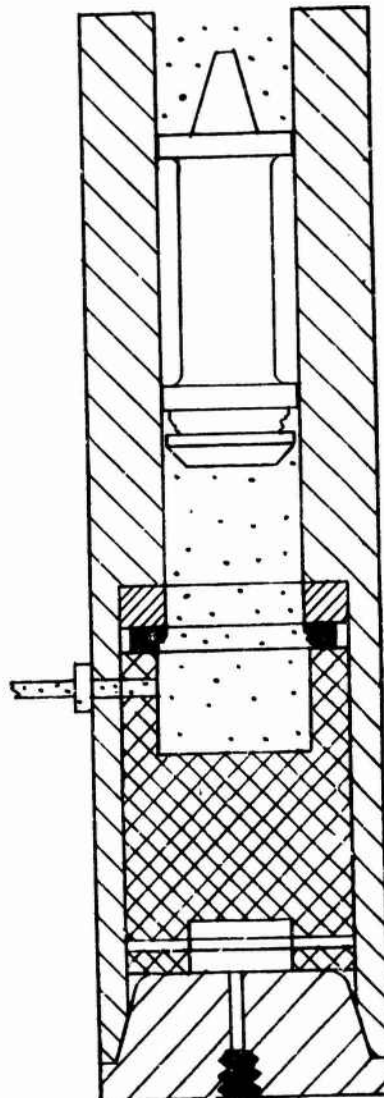


Figure 3. Exploded View of Air Gun Release Mechanism



A. Projectile and Diaphragm in Place Prior to Rupture



B. Diaphragm Ruptured and Projectile Accelerated Down Barrel

Figure 4. Diaphragm Method of Firing the 5 Inch Air Gun

assembled as part of the piston assembly. High pressure air is introduced on the breech side of the assembly, and when the force on the piston exceeds the shear strength of the diaphragm, the diaphragm shears through the groove. An unbalanced force then acts on the piston and it is propelled down the barrel. Very high acceleration levels, up to 35,000 g's, can be obtained with this method. Various peak g levels are produced by varying pressure, piston weight, and diaphragm thickness.

A typical acceleration time history obtained using the diaphragm method is shown in Figure 5. The measurement was made with an Endevco Model 2225 accelerometer mounted on the piston and an MB Zero Drive signal conditioning system, the system frequency response being flat to 20,000 Hz. The accelerometer lead was brought out through a port in the gun about six feet down the barrel. As the piston passes this point in the gun, the lead is sheared, usually resulting in a violent oscillation on the record. With this measurement technique only the first few feet of the acceleration-time history is obtained.

A comparison of the characteristics of gunfire shock and the simulation provided by the diaphragm method in the 5 inch air gun shows some significant deficiencies in this test method. The rise time to the peak acceleration in the air gun is shorter than in the actual gun, and there is no significant dwell time around the maximum level. The acceleration decays much faster in the air gun, and as a result, the maximum velocities are substantially lower than in gunfire shock. In addition, there is little that can be done to control the shape of the shock pulse to simulate the different shocks produced by various weapons. Because of the difference in acceleration-time histories, it is doubtful that fuzes and their internal components respond dynamically the same in the air gun as they do during actual gunfire shock. Some components would be overtested, some would be undertested. Since the air gun has a smooth bore, any effects of rotation are entirely absent in this laboratory simulation. Although present air gun tests are valuable, and do subject the test item to realistic acceleration levels, a more accurate simulation of gunfire shock is clearly desirable.

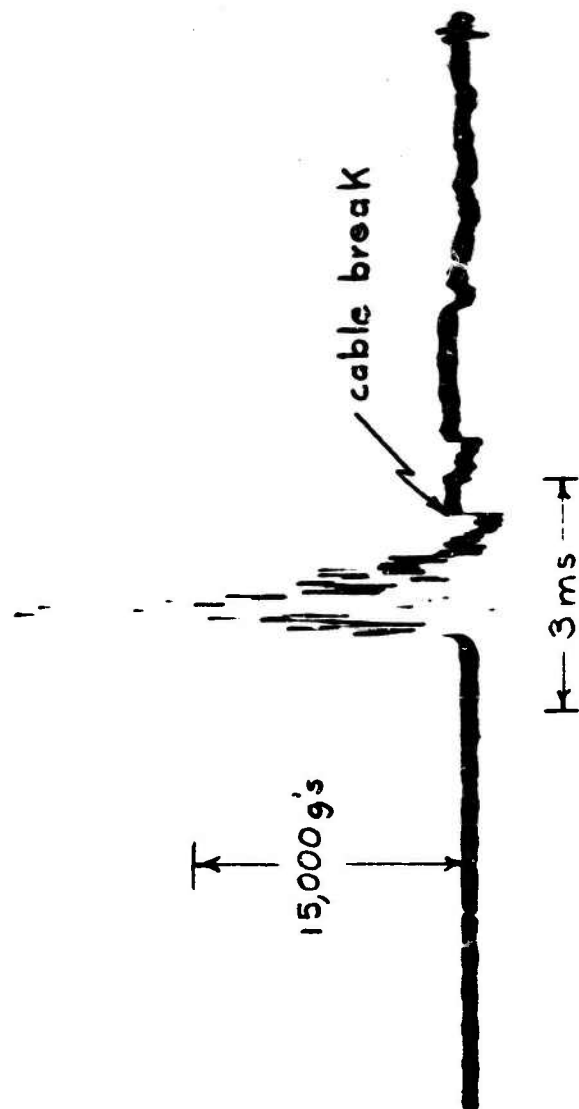


Figure 5. Measured Acceleration Time History Using Diaphragm Firing Method

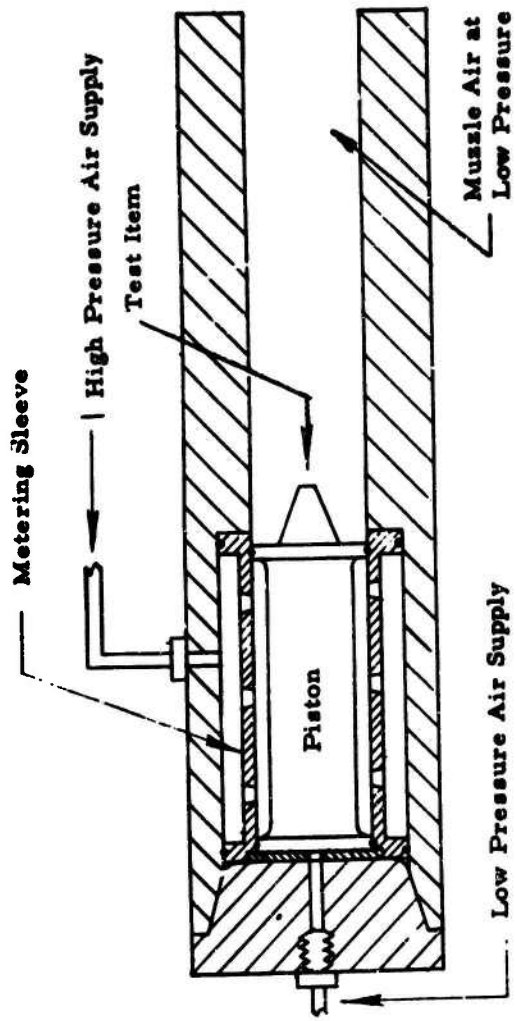
METERING SLEEVE FIRING METHOD

There are many built-in physical parameters of the 5 inch gun which seriously limit its ability to develop an improved simulation of gunfire shock. In an effort to obtain more realistic acceleration-time histories in the existing system, experiments were made with various methods for developing controlled shock pulses. This resulted in a test method using a metering sleeve to control the rate at which high pressure air in an annular volume flows into the gun, where it acts on the piston. The metering sleeve has a number of tapped holes which can be plugged or left open in order to control the air flow required for a given shock. Figure 6 shows the operation of the metering sleeve method.

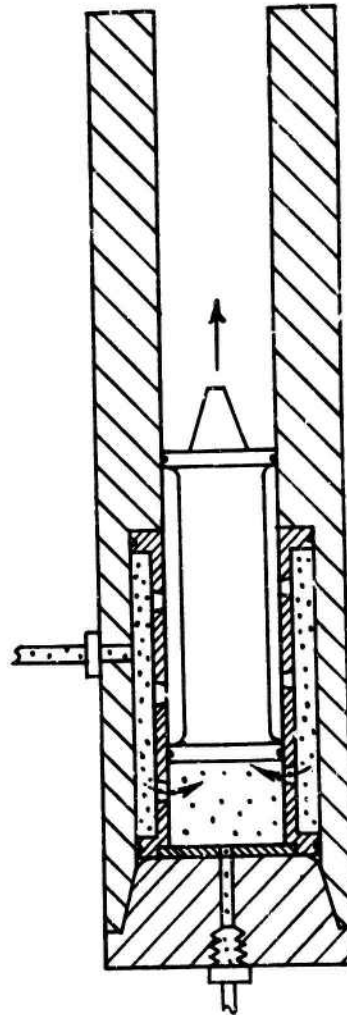
Initially the piston is sealed against the back of the sleeve and high pressure air fills the annular volume. To start the action, a jet of low pressure air pushes the piston forward until the first row of holes in the metering sleeve is uncovered. The high pressure air then flows through these holes and behind the piston, and begins accelerating the piston forward. As the piston moves forward, more holes are uncovered, allowing more air to flow into the gun, and so the process continues during the controlled portion of the pulse. At the end of the controlled portion of the pulse, the pressure in the annular volume and behind the piston is usually assumed to be the same. Thereafter, the pressure behind the piston and hence the acceleration decays exponentially. In the simulation of gunfire shock, the metering sleeve would be used to control the shock pulse up to the maximum level, and then allow the gas to expand with no further control. If a sufficient high pressure volume is available, the result should be a reasonably good simulation of gunfire shock.

In order to use the metering sleeve technique, a method is required for determining the relationship between orifice area and piston displacement to produce a desired shock pulse. Reference 2 illustrates the method, and determines the required pressures and orifice arrangement for a 5000 g pulse with a 3 ms rise time. The

²J. Wiland, "Shock Pulse Shaping in an Air Gun", Frankford Arsenal Report T68-12-1, Nov. 1968.



A. Piston and Metering Sleeve Prior to Firing



B. Piston During Controlled Portion of Shock Pulse

Figure 6. Metering Sleeve Method for Firing Air Gun

calculation procedure is a simplified, approximate method, and might be viewed as a first try at producing a desired pulse, which can be improved by experimentally modifying the hole pattern.

Figure 7 shows the resulting shock pulse obtained in the 5 inch air gun using the metering sleeve. The metering sleeve method has been found to be particularly useful in testing setback pins. These mechanisms require not only that the acceleration be a certain level, but that it be sustained long enough to cause the required displacements of components to perform the arming function. Testing setback pins using the diaphragm method has generally met with failure because realistic time durations, absolutely necessary for arming, are not attained.

DESIGN APPROACH FOR THE 155mm BALLISTIC SIMULATOR

Because of the shortcomings of the present system in simulating artillery gunfire shock, development of the 155mm Ballistic Simulator was undertaken. This system was designed to provide a more realistic simulation of the gunfire shock environment, with correspondingly higher velocities, and would include the important parameter of rotation. The concept evolved was to use as the primary component a 155mm gun with the rifling intact, modify the breech to accept a metering sleeve, and add a closed end extension of sufficient length to keep deceleration to an acceptable level. The piston design would include a preformed rotating band, and provision would be made to use either air or helium as the driving fluid. Helium, being a light gas, would produce higher velocity levels than can be achieved with air as the high pressure fluid.

Some of the parameters of the new simulator were determined using the characteristics of gunfire shock as a basis. Since the peak acceleration in ballistic shock is nearly always reached within the first 18 inches of travel, the metering sleeve (which would control acceleration up to the maximum level) should be at most 18 inches long. The breech area of the new system was thus designed to provide for an 18 inch metering sleeve.

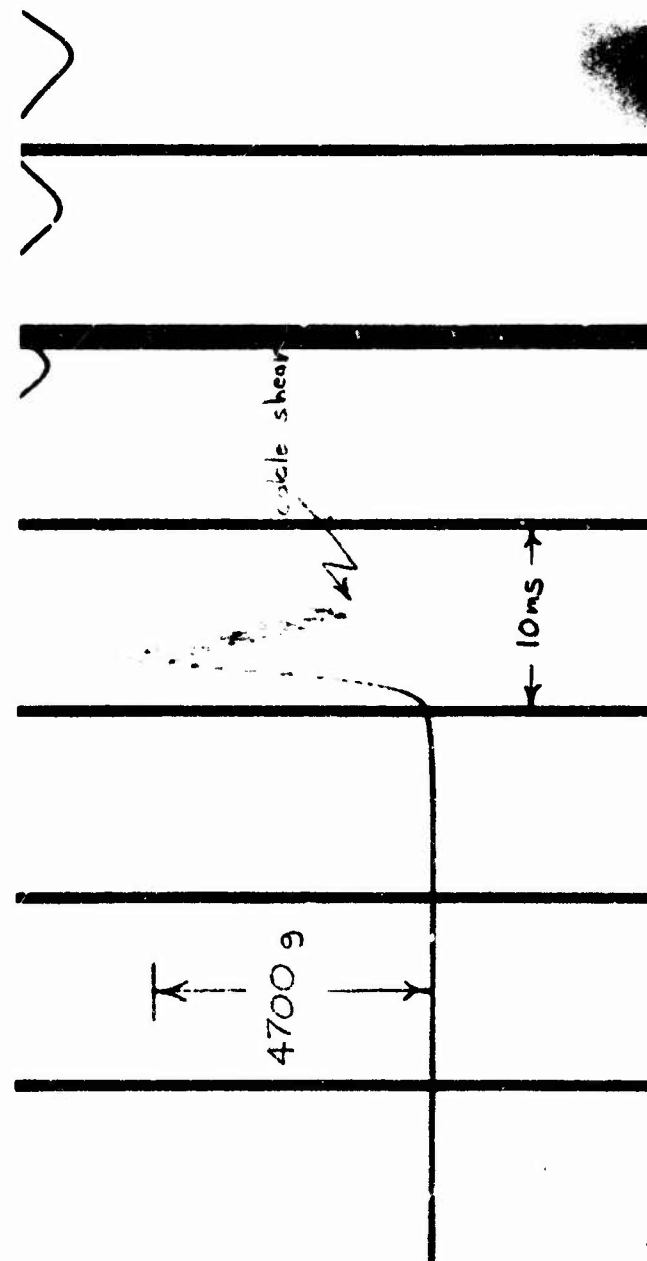


Figure 7. Half-Sine Shock Obtained Using Metering Sleeve Firing Method

Maximum Length of Metering Sleeve = 18 in.

Projectile acceleration in gunfire shock is typically positive throughout the length of the weapon. Thus, to provide a reasonable simulation of this environment, the high pressure volume of the new system should be sufficient to provide positive pressure for a distance of about 25 feet. The initial high pressure annular volume necessary to achieve this, using helium as the gas, is calculated assuming an adiabatic process and 2 percent cushion pressure.

$$PC_o VC_o^K \Big|_{x=0} = .02 PC_o \left[VC_o + A x \right]^K \Big|_{x=25}$$

where PC_o = initial high pressure, lb/in²

VC_o = initial high pressure volume, in.³

K = ratio of specific heats, 1.66 for helium

A = Area of gun, 29.2 in.²

X = piston displacement, in.

$$PC_o VC_o^{1.66} = .02 PC_o \left[VC_o + 25 (12) (29.2) \right]^{1.66}$$

and solving:

High Pressure Volume = 917 in.³

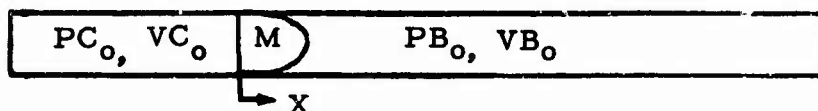
Assuming the outside diameter of the metering sleeve is 7.1 inches, the diameter D_H of the high pressure volume is determined as follows:

$$VC_o = 917 = \frac{\pi}{4} \left[D_H^2 - 7.1^2 \right] (18) \quad (18)$$

and solving:

Diameter of High Pressure Volume = 10.75 inches

In order to determine the required cushion volume and approximate deceleration levels, the gun is modeled as a two chamber system.



$$\text{Acceleration } \ddot{x} = \frac{A}{M} \left[\frac{PC_o VC_o^K}{(VC_o + Ax)^K} - \frac{PB_o VB_o^K}{(VB_o - Ax)^K} \right]$$

where PB_o = initial cushion pressure

VB_o = initial cushion volume

integrating to obtain velocity \dot{x}

$$\dot{x} = \left\{ \frac{2}{M(K-1)} \left[PC_o VC_o \left(1 - \frac{VC_o^{K-1}}{(VC_o + Ax)^{K-1}} \right) + PB_o VB_o \left(1 - \frac{VB_o^{K-1}}{(VB_o - Ax)^{K-1}} \right) \right] \right\}^{1/2}$$

This expression is used to determine the total cushion volume required; this volume including the gun and extension tubes plus a muzzle tank. The gun length was set at 145 feet, nearly 3 times as long as the present 5 inch air gun.

$$\text{Length of Gun} = 145 \text{ ft.}$$

Assume the projectile is to stop at about $X = 100$ feet using an initial cushion pressure which is 2 percent of the initial chamber pressure. Setting the expression for velocity equal to zero and $K = 1.66$.

$$0 = 917 \left[1 - \frac{917^{K-1}}{[917 + 30.2(100)(12)]^{K-1}} \right] + .02 V_{B_0} \left[1 - \frac{V_{B_0}^{K-1}}{(V_{B_0} - 36240)^{K-1}} \right]$$

and solving: $V_{B_0} = 72800 \text{ in.}^3 = 42 \text{ ft.}^3$

The volume of the gun plus extensions is

$$V_{\text{gun}} = 145 \left(\frac{1}{144} \right) \left(\frac{\pi}{4} \right) (6.2)^2 = 30.4 \text{ ft.}^3$$

The volume of the muzzle tank should be about 11.6 ft.^3 , and we elected to increase this to 15 ft.^3 .

$$\text{Volume of Muzzle Tank} = 15 \text{ ft.}^3$$

With the volumes of the system now determined, the expression for acceleration can be used to estimate the maximum deceleration of the projectile as a percentage of maximum acceleration.

$$\frac{\ddot{X}}{PC_0 \frac{A}{M}} = \frac{VC_0^K}{[VC_0 + Ax]^K} - \frac{.02 VB_0^K}{[VB_0 - Ax]^K}$$

for $VC_0 = 917 \text{ in.}^3$, $VB_0 = 45.4 \text{ ft.}^3$, $X = 100 \text{ ft.}$, $K = 1.66$

$$\frac{\ddot{X}}{PC_0 \frac{A}{M}} = -.055$$

Because of the metering of the gas

$$\ddot{X}_{\text{max}} \approx \frac{1}{2} \frac{PC_0 A}{M}$$

$$\frac{\ddot{X}}{\ddot{X}_{\text{max}}} = -.11$$

Maximum Deceleration \approx 11 percent Maximum Acceleration

One of the concerns during development of the system was with the amount of energy required to spin up the projectile in addition to imparting linear velocity. The 155mm gun tube has a twist of 1 turn in 25 calibers. The tangent of the angle of twist θ is

$$\tan \theta = \frac{\pi}{n} = \frac{\pi}{25} = .126$$

where n = number of calibers in length for one turn of groove

The angular velocity ω in radians/sec. is

$$\omega = \frac{2 v \tan \theta}{d}$$

where v = velocity of translation of projectile, ft/sec.

d = diameter of bore, ft.

The ratio of rotational to linear kinetic energy of the projectile, assuming it is a uniform cylinder, is

$$\begin{aligned} \frac{\text{rotational K. E.}}{\text{linear K. E.}} &= \frac{\frac{1}{2} I \omega^2}{\frac{1}{2} m v^2} = \frac{\frac{1}{8} m d^2 \left(\frac{4 v^2}{d^2} \tan^2 \theta \right)}{m v^2} \\ &= \frac{\tan^2 \theta}{2} = .008 \end{aligned}$$

The rotational kinetic energy of the projectile is thus about 1 percent of the linear kinetic energy, and therefore can reasonably be neglected in designing the system.

The recoil distance of the simulator, which in the actual 155mm gun is about 5 feet, is estimated based on momentum considerations, as follows:

$$v_r W_r = v_p W_p + v_g W_g$$

where v_r = velocity of recoiling parts, fps.

W_r = Weight of recoiling parts, 14000 lbs.

v_p = velocity of projectile; for air about 1000 fps.

W_p = Weight of projectile, 15 lbs.

v_g = velocity of gas; for air about 1000 fps.

W_g = Weight of gas; use 20 lbs.

$$\text{solving } v_r = \frac{1000(15) + 1000(20)}{14,000} = 2.5 \text{ fps.}$$

The energy of recoil E_r then is

$$E_r = \frac{1}{2} \frac{W_r}{g} v_r^2 = \frac{1}{2} \left(\frac{14000}{32.2} \right) 2.5^2 = 1360 \text{ ft-lb}$$

The recoil distance L is given by

$$L = \frac{E_r}{F_r}$$

where F_r = recoil force, 73,500 lb; Ref. Dwg. 7148374

$$L = \frac{1360}{73,500} = .0185 \text{ ft.} = .22 \text{ in.}$$

The recoil distance will be somewhat higher than this because full recoil force does not develop immediately. The actual distance might be expected to be twice the estimated value, i. e., 0.5 inch.

Recoil Distance \approx 0.5 in.

DESCRIPTION OF 155mm BALLISTIC SIMULATOR

Figure 8 shows an overall view of the breech end of the 155mm Ballistic Simulator including the recoil mechanism and gun cradle. Figure 9 shows the muzzle end of the 145 foot long facility as it extends out of the building. The muzzle tank is suspended under the tube and includes one way valves which allow flow into the tank, but prevent gas flow out of the tank. This tends to minimize the

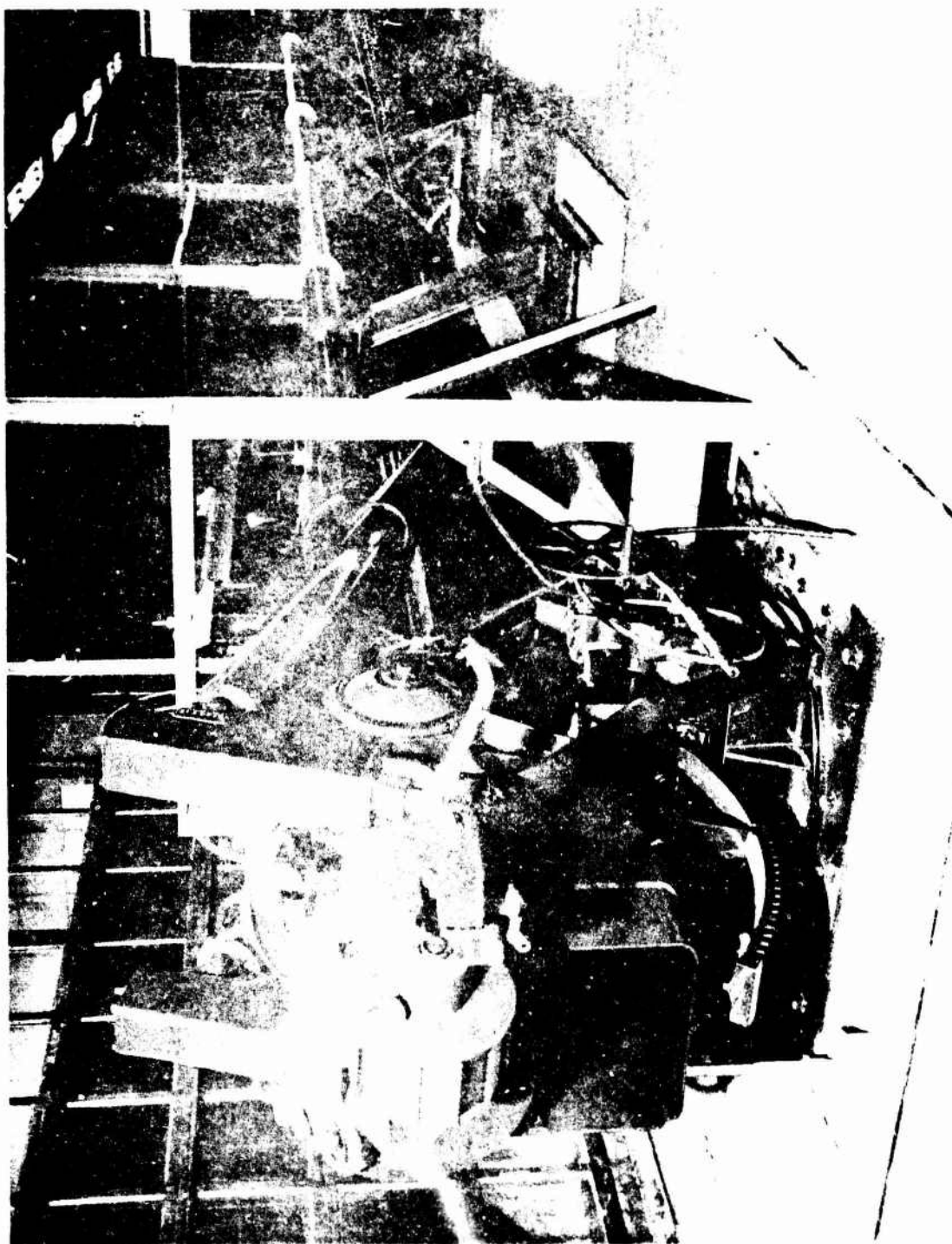


Figure 8. 155 mm Ballistic Simulator - Breech End

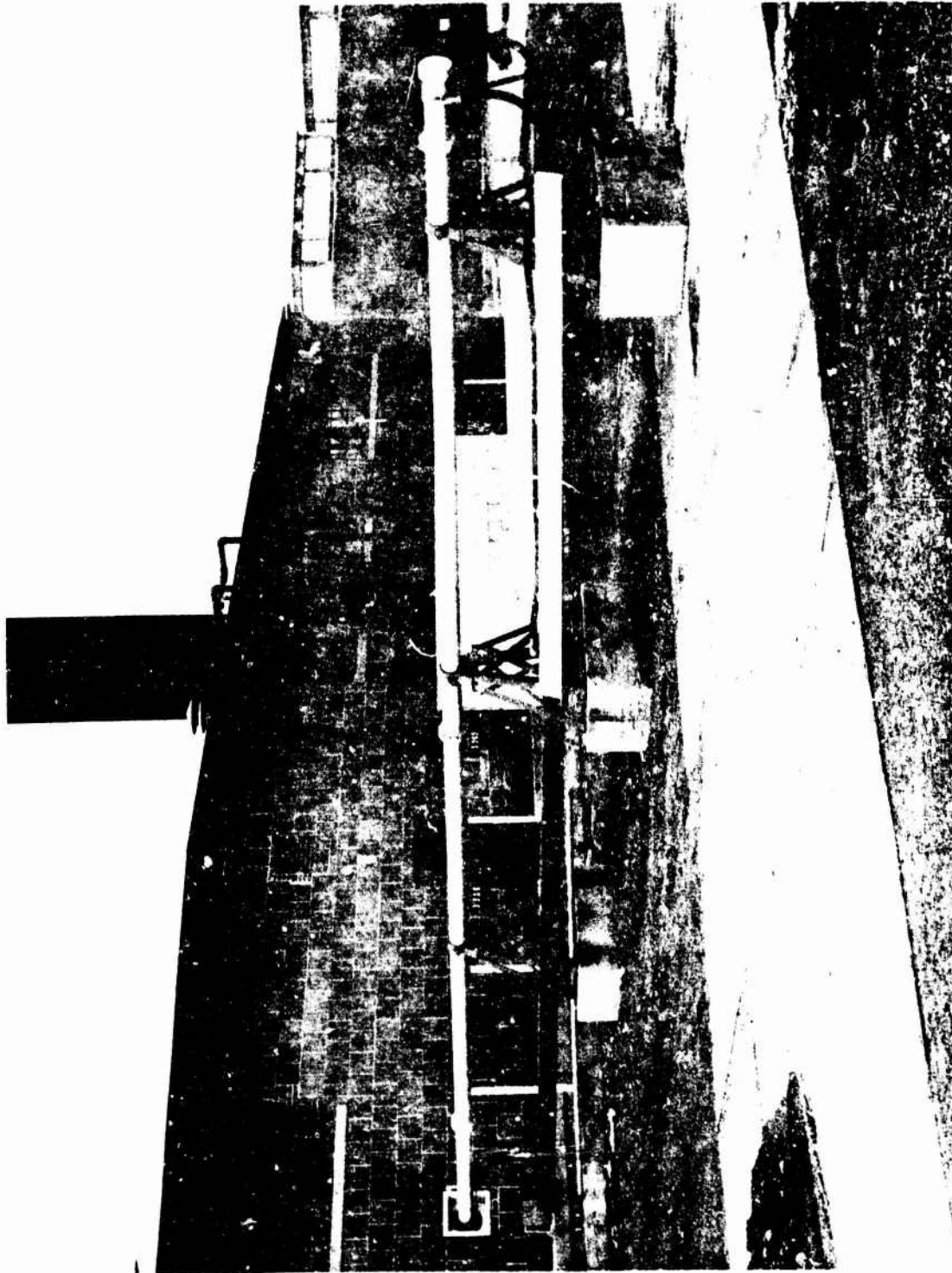


Figure 9. 155 mm Ballistic Simulator - Muzzle End

oscillations of the piston. The extension tubes are smooth bore and on the muzzle end of the system is a breech where the piston is removed after firing. Because of the rifling in the gun, the projectile cannot be brought back to the breech end for removal as is done in the 5 inch air gun. Figure 10 shows the control console from which both the 5 inch air gun and the 155mm Ballistic Simulator system can be operated. For safety, the design incorporates pressure transmitters so that only a fraction of system pressures exist at the console.

Figures 11 and 12 show the breech components, the breech block, metering sleeve, and the original two piece piston. Rubber "O" rings are used to seal the high pressure from the gun and piston before firing. The two piece piston design was selected on the premise that the molded rotating band would wear and should be easily replaceable. The rotating band material was fabricated from glass reinforced nylon, and assembled attaching to the piston by means of a spline. The piston weighed 13 lbs and was 12 inches long between the riding surfaces, which meant a shock pulse could be controlled for this distance, and included provision for mounting a standard fuze.

The two piece piston proved unsuccessful, as it was very difficult to prevent the rotating band section from separating from the main body of the piston. It was theorized that the high pressure during firing was getting between the two sections forcing them apart. Incorporating an "O" ring seal between the components helped considerably, and with it, firings were made up to 8000 g's. Continual reinforcement of the retaining components was necessary, however, to prevent separation but this added additional weight to the piston. After a 3/4 inch aluminum ring which retained the rotating band had failed, it was decided that the projectile should be a one piece design.

The one piece piston design is shown in Figures 13 and 14. It incorporates 48 rectangular nylon keys bonded to slots in the body of the piston to engage the rifling. The projectile material is 75ST6 aluminum, and the total weight is 15.8 lbs. This design has thus far been successful, but is still somewhat heavy. The projectile is subjected to its highest stresses just before firing as it experiences both hoop compression stresses and tension stresses resulting from the pressure acting on the flanges. Future effort will have to be directed towards minimizing the projectile weight.

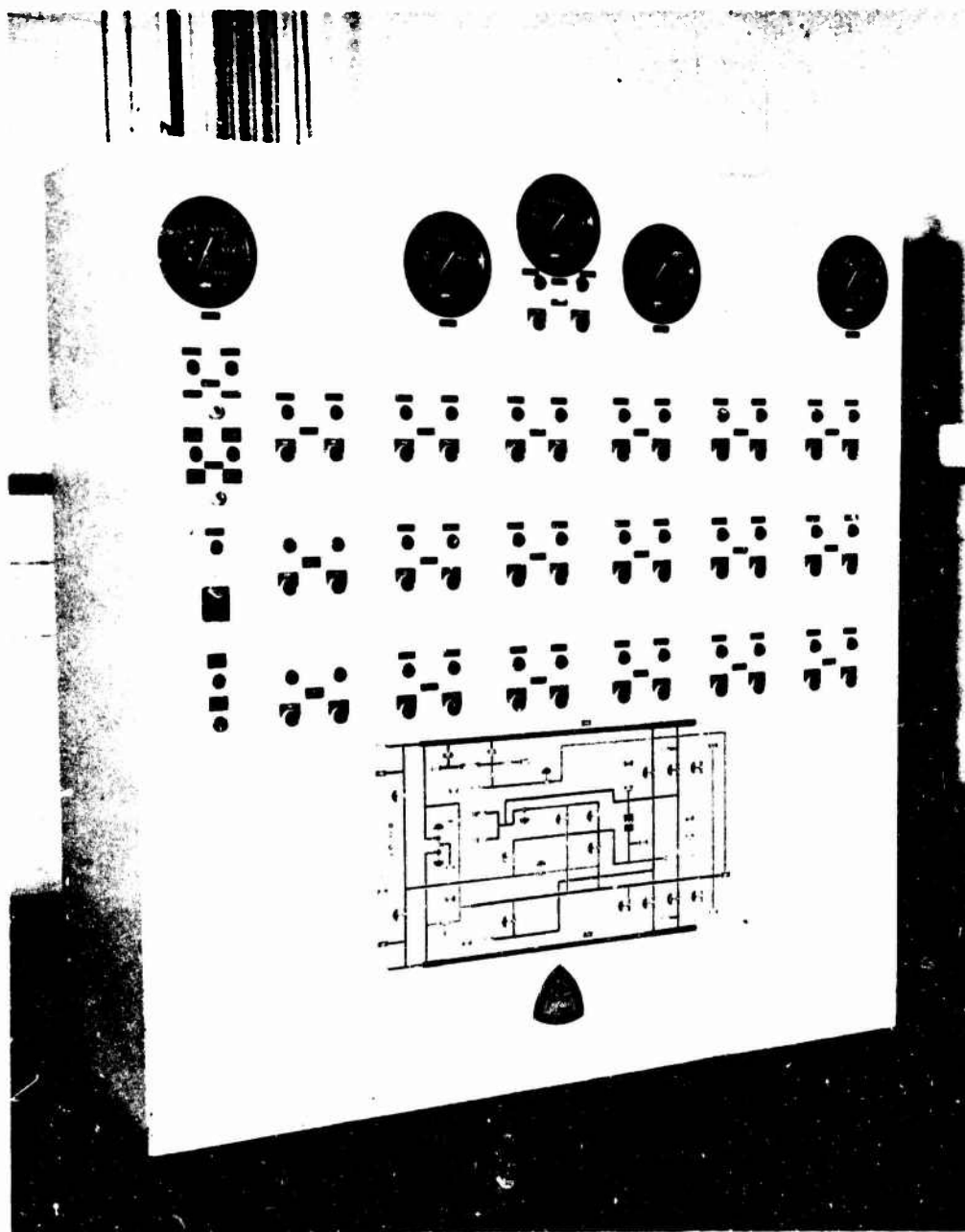


Figure 10. Control Console for 155 mm Ballistic Simulator

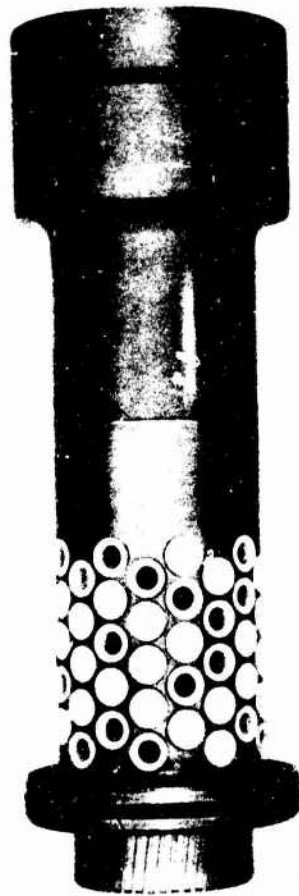


Figure 11. Assembled View of Breech Components - 155 mm Ballistic Simulator

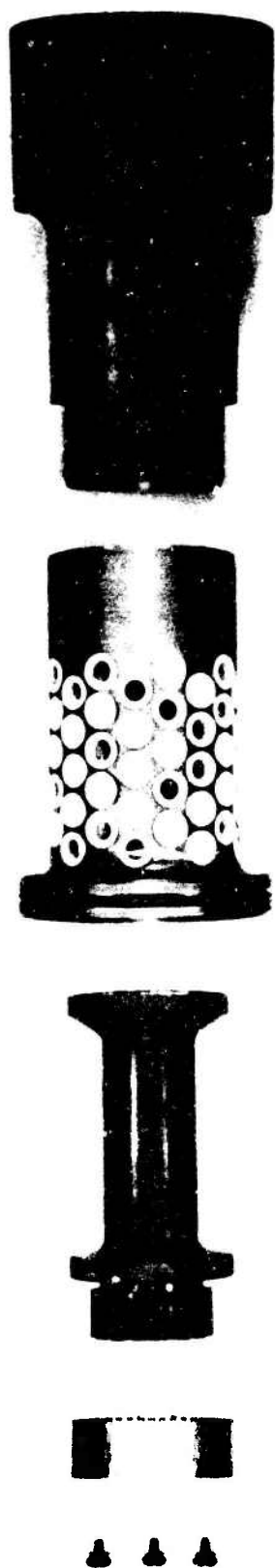


Figure 12. Exploded View of Breech Components - 155 mm Ballistic Simulator

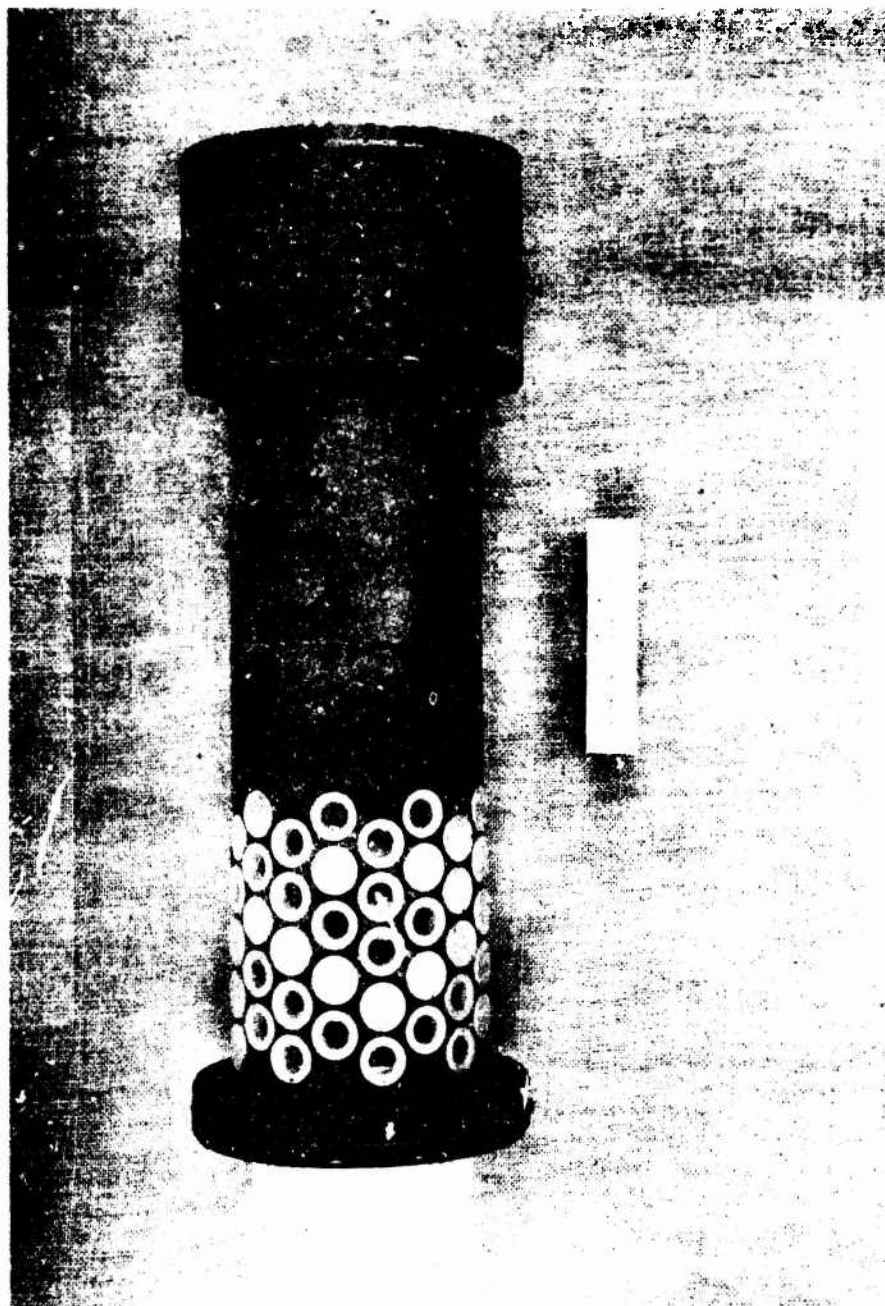


Figure 13. Assembled View of Breech Components with One Piece Piston

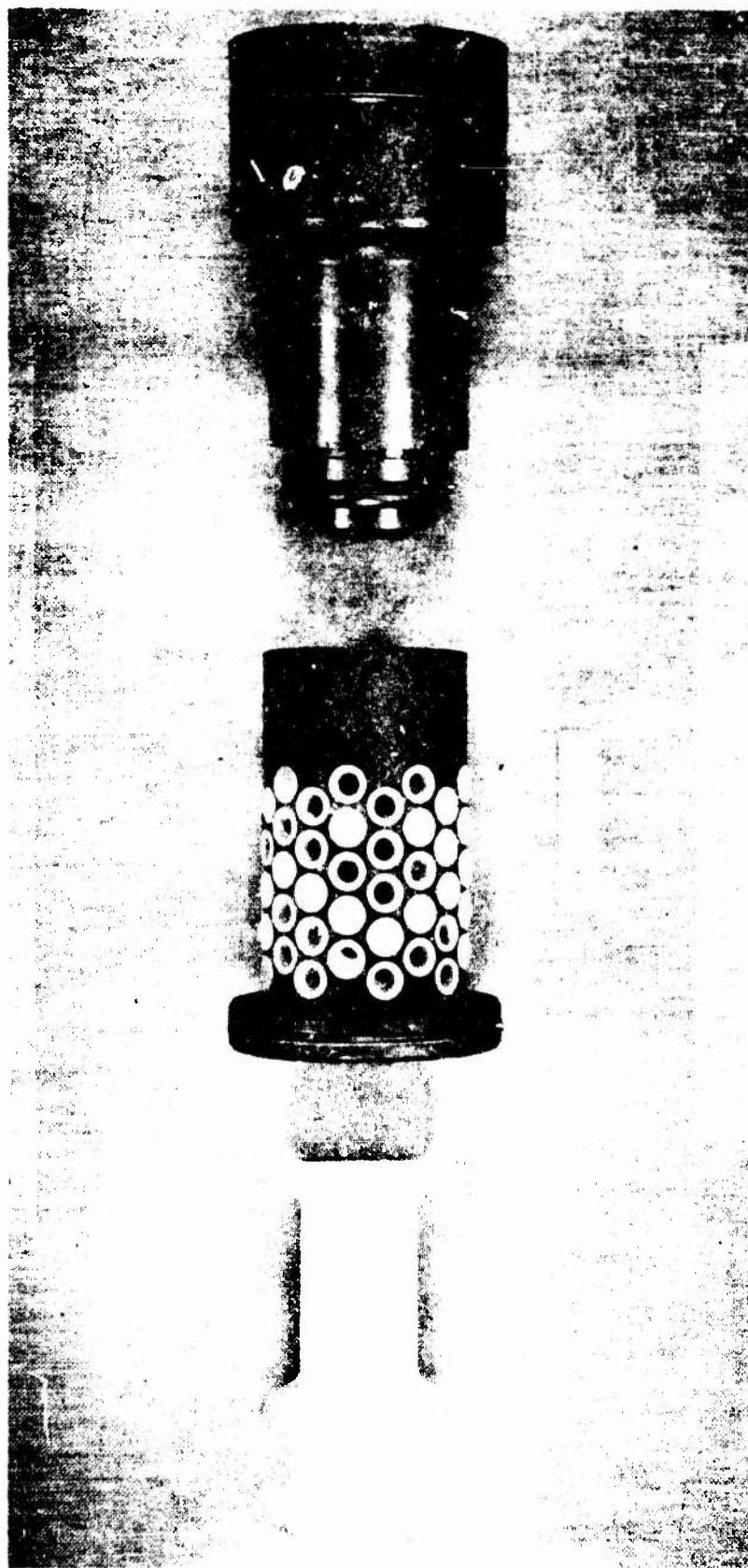


Figure 14. Exploded View of Breech Components with One Piece Piston

TEST RESULTS WITH PRESENT SYSTEM CONFIGURATION

Figures 15 to 18 show the measured acceleration time histories from a series of firings up to 10,000 g's using the one piece piston. The measurements were obtained using the hard wire technique discussed previously with an Endevco Model 2225 accelerometer mounted on the piston.

An MB Zero Drive signal conditioning system was used, with a flat frequency response up to 10,000 Hz. Due to the cable being sheared, only the initial portion of the acceleration-time history can be shown using this measurement technique. It was our intention to use a telemetry system in order to measure the entire time history, but various difficulties have so far prevented satisfactory measurements with the telemetry system. These truncated measurements are sufficient however to demonstrate the magnitudes and general character of the time histories produced in the simulator.

The 3000 g shock shown in Figure 15 is the lowest level shock shown and therefore more of the time history is seen than in the higher level shocks. In its general shape the acceleration-time history can be seen to be a good representation of typical artillery ballistic shocks. It rises approximately sinusoidally to the peak value followed by an exponential decay, and is essentially the type of shock desired from the system. Although less of the time history of the higher level shocks is seen, it should exhibit the same general characteristics. A comparison of a diaphragm shock from the 5 inch gun, Figure 5, with those from the 155mm simulator illustrates the longer durations achieved in the new system. When the helium compressor becomes available in the near future, even longer duration shocks should be produced.



Figure 15. 3000 g Firing Shock - 155 mm Ballistic Simulator

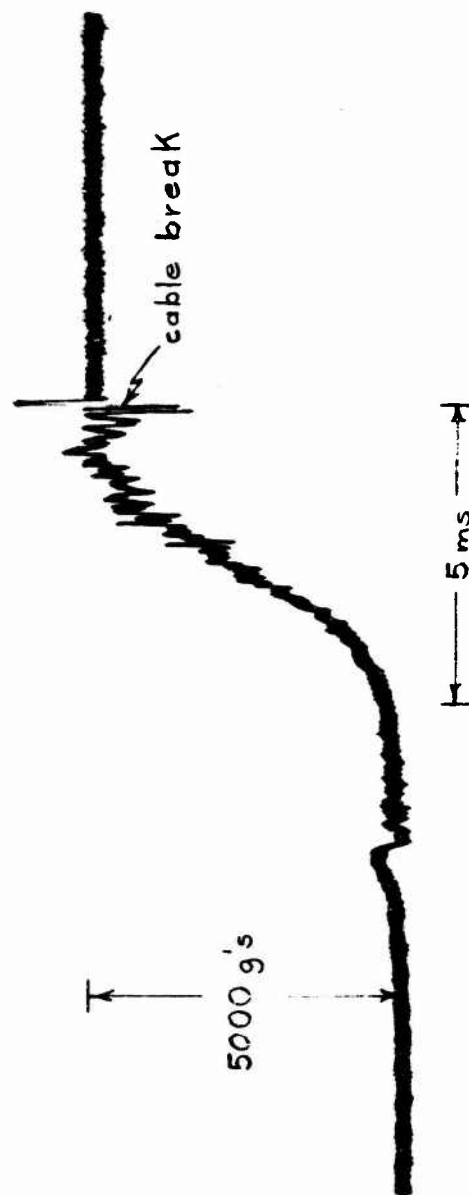


Figure 16. 5000 g Firing Shock - 155 mm Ballistic Simulator

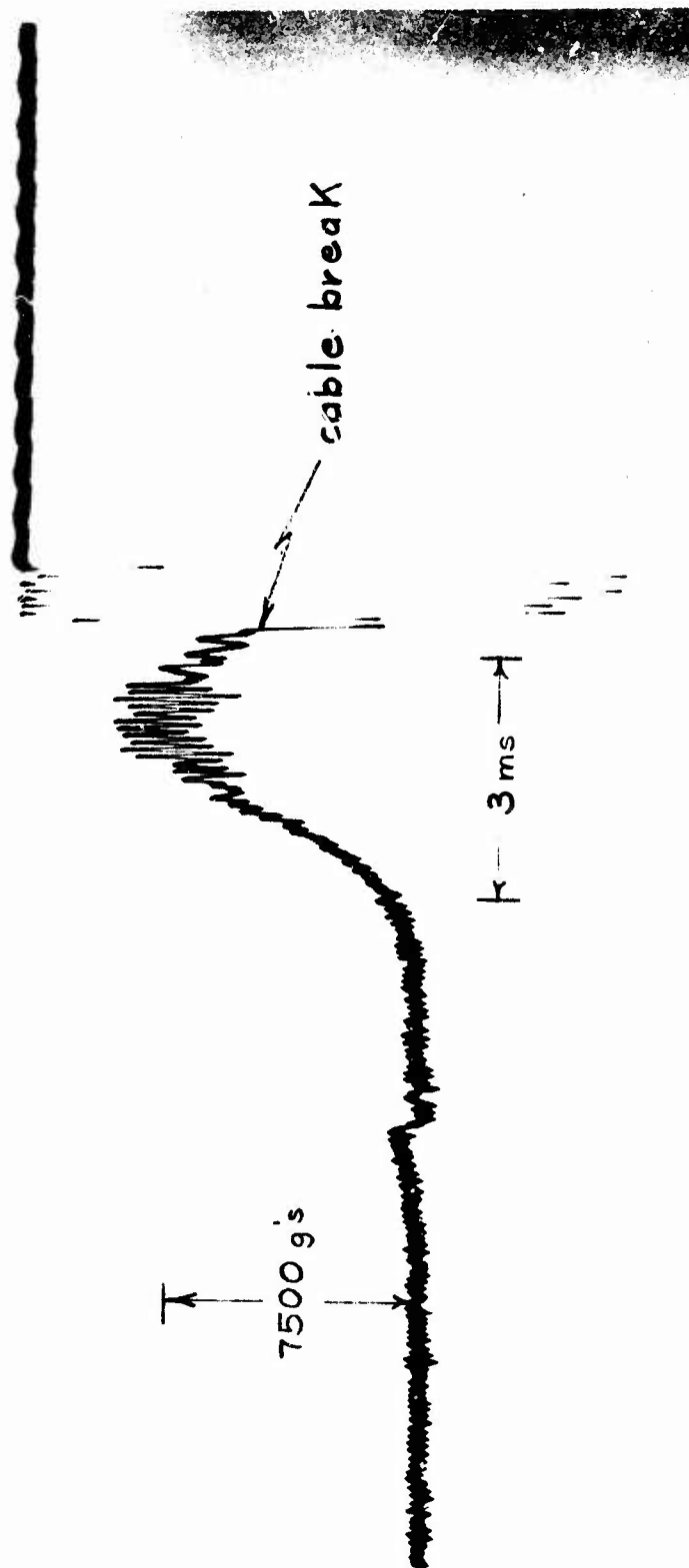


Figure 17. 7500 g Firing Shock - 155 mm Ballistic Simulator

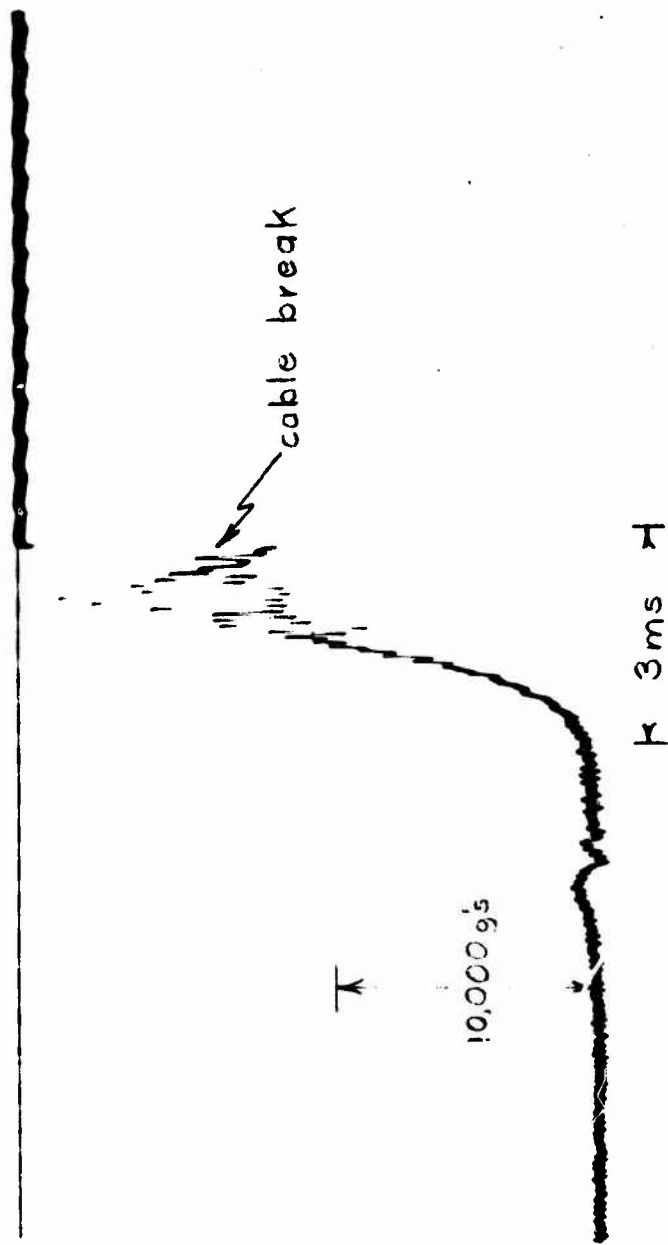


Figure 18. 10,000 g Firing Shock - 155 mm Ballistic Simulator

SUMMARY

This report has presented the progress thus far made in perfecting the 155mm Ballistic Simulator. Acceleration levels with present hardware are limited to about 12,000 g's. This level is sufficient, however, for simulating the environment for many firing conditions, and within this range is a decided improvement over present laboratory fuze test methods. In addition, the important parameter of rotation is included in the simulation. Firing the helium should expand the range of the system, insofar as it will produce longer duration pulses.

The development of a major facility like the 155mm Ballistic Simulator is a large undertaking that required many difficult decisions. Generally, the results show that the system does work and does generate ballistic type shocks. The accomplishments to date are: (1) the firing cycle goes well, (2) the rubber "O" rings will seal pressure in excess of 12,000 psi, (3) the metering sleeve satisfactorily shapes the initial part of the time history, (4) the piston stops without impacting the end of the gun or reentering the rifled section and is easily recovered, (5) cushion pressures less than 1.5 percent of firing pressure have been satisfactory, (6) the one way valves in the muzzle tank operate well, (7) and the nylon keys for the rotating band withstand the forces due to angular acceleration without failure. Some disadvantages are: (1) the projectile design is too heavy and reduces the maximum acceleration level, (2) the durations of the acceleration time history, hence velocity, at high levels are lower than desired, (3) and with the present measurement technique, the entire shocktime history is not measured.

The use of helium in the near future should effect longer shock durations, and steps are being taken to obtain satisfactory telemetry measurements of the entire acceleration time history. A significant reduction in the weight of the piston may be the most difficult improvement to achieve. As time and resources permit, future efforts will be directed at investigating alternative materials and/or configurations to attain lower piston weights.

CONCLUSIONS

The 155mm Ballistic Simulator is capable of producing a more realistic simulation of gunfire shock than that produced by the 5 inch air gun, and simultaneously includes the important parameter of rotation. The maximum acceleration level of 12,000 g's attained to date is sufficient for simulating many firing conditions, and hopefully will increase with future refinements. The improved simulation of gunfire shock will permit more items to be tested in the laboratory, with greater confidence than is now possible, and at less expense. Thus, there will be reduced requirements for field firing to assess the reliability ammunition components.